3.1.2. Data System Spectrum Efficiency

It is important to recognize that RF bit rate alone does not determine mobile data system throughput, and bits per second per Hz is only one of a number of important factors affecting spectrum efficiency in digital communications.

A more meaningful measure of spectrum efficiency is the amount of useful information reliably transferred per unit bandwidth per unit time over a desired coverage area.

For a wide variety of applications, this definition is best fulfilled by packet data communications. Section 2.1.2.3. discusses a practical scenario in which a packet data system operating on a 5 kHz channel can realize over one hundred times as much useful information throughput per Hz as a 25 kHz voice system.

The following sections look at a number of packet data applications, with widely varying message sizes. The practical examples draw on UPS experience and planning, but the messages shown here are generic in nature. UPS expects mobile packet data use to become increasingly common in the next several years.

For these applications, average RF channel time per message for a narrowband system is compared to examples of wider band mobile data systems. To compare systems of different bandwidths, the time bandwidth product of spectrum resources used for each data transfer is evaluated. Coverage parameters are also compared, since both wide area coverage for suburban and rural areas and frequency reuse for dense RF traffic zones are important aspects of overall spectrum efficiency.

Next, the amount of time consumed for these message sizes with different narrowband technologies is considered in order to compare attainable throughput. Coverage parameters are also compared for the narrowband options.

Tables 2, 3, 4, and 5 summarize the comparison of throughput, coverage, use of spectrum resources, and relative equipment complexity for these examples.

Full analysis of channel access time and message completion delay, or latency, are beyond the scope of the UPS Reply Comments, but the literature offers helpful background discussions, e.g. [21] and [22]. Multiple access systems vary greatly in stability and practical maximum loading. However, the amounts of RF air time consumed for typical messages give excellent indications of access time, delay, and maximum loading for one system compared to another.

and BER vs. E_b/N_0 are very nearly equal for the UPS system when operated at 4 kbps.

Based on [9], the average of measured C/N and C/I at 10^{-2} BER, i.e. about 95% FEC block success, gives 12.5 dB as the E_b/N_0 threshold for excellent coverage for the UPS system in additive white Gaussian noise (AWGN) conditions. As discussed in 2.1.2.2., recent II Morrow lab results show an improvement of three dB is attainable over the results in [9] at 10^{-2} BER. In Rayleigh fading, E_b/N_0, C/N, and C/I required for 10^{-2} BER increase by about 10 dB for the UPS system. [9]

For other modulations and systems, the comparison uses sensitivity, BER vs. C/I, BER vs. C/N, BER vs. E_b/N_0, or other parameters as publicly stated or available in the literature.

3.2.2. Path Loss

Land mobile signal propagation is well known for its variability. As rules of thumb in comparing coverage, we estimate path loss per octave of distance at about 10 dB under typical AWGN conditions, up to about 20 dB per octave of distance for typical Rayleigh faded conditions. More detailed analyses, e.g. Longley-Rice computations, are beyond the scope of this discussion.

3.2.3. Peak to Average Power Ratio

Link performance factors such as sensitivity, BER vs. E_b/N_0, BER vs. C/N, and BER vs. C/I are based on average signal power. Power amplifiers are specified in terms of peak envelope power (PEP). We compare relative coverage capabilities based on equal transmit PEP, and equivalent HAAT, antennas, RF cables, etc.

For FM, or, more generally, continuous phase modulation (CPM), i.e. constant envelope methods, PEP equals average power. For linear modulations, the ratio of peak to average power is not constant, and depends on modulation, or from speaker to speaker with analog voice. As discussed in the following sections, for various linear data modulations, average power varies from about two to five dB less than peak power.

3.3. Packet System Throughput Factors

RF bit rate is only one of several important factors affecting packet system throughput. Other factors include: multiple access methods; demodulation delays; FEC; error detection; ARQ; and other channel control signaling, such as acknowledgements.

Digital voice communications generally employ some form of error correction. When error correction is not totally successful, some loss of bits or blocks is acceptable, but if too many errors occur, the remedy is that the users repeat portions of conversations.

Packet data systems can compress important messages into very small portions of time. For many applications, reliability is vital, and every data bit error must be detected and corrected before a message or message segment transfer can be considered complete. The UPS system design, for example, keeps undetected message error rates below 10^9.

The art of effective mobile packet data system design is to attain reliability with the smallest amount of added time for channel access, FEC, error detection, ARQ, and acknowledgements. Fig. 1 in [9] illustrates a time line for a 100 byte message transfer with efficient burst signaling. The application is package tracking, a point of sale data transfer networked into a nationwide data base.

3.4. Packet Data Applications Examples

UPS's experience and planning provide practical examples of data communications. These examples are generic in nature, with relevance to applications for different businesses, industries, and public safety organizations.

3.4.1. 100 Byte Package Tracking Message

Package tracking is one of the most important mobile radio applications for UPS.

For this example, the critical path for determining system capacity is the air time consumed on the inbound (reverse) RF link. For mixtures of inbound and outbound (forward link) messages and control signaling, the analysis can be applied to whichever link is more heavily loaded. In heavy RF traffic, the UPS system manages multiple concurrent message transactions to make use of all portions of time on both the outbound and inbound links. [9] It is important to note that many data systems make little or no

simultaneous use of inbound and outbound frequencies. In these cases, all time consumed on both the inbound and outbound links for the message under consideration counts as critical path time.

For the UPS system, under typical loading conditions, and with a 95% FEC block success rate, total elapsed time for channel access and reliable, acknowledged transfer of a 100 byte package tracking message through the RF link from the mobile to the base is about one and a half to two seconds. However, critical path air time is only about 540 ms. This 100 byte message can carry important information on several parcels and customers.

Because of the importance of package tracking for UPS, this application serves as a benchmark for system capacity. Even with the most intensive potential package tracking message scenarios, involving ten or more message transfers per mobile per hour, UPS's narrowband digital FM systems can serve up to six hundred package vehicles on a single 5 kHz channel, with low delay and stable throughput.

3.4.2. Vehicle Tracking

UPS plans for vehicle tracking include long haul vehicles, on call pick up vehicles operating within a metropolitan area, and precise positioning within hub yards.

Many vehicle tracking applications will be able to use specially compressed position reports, sent without channel contention, consuming as little as 24 ms of critical path air time using the UPS system. Allowing for 95% FEC block success brings the average up to 25 ms per position report.

3.4.3. Hub Yard Shifter Communications

Shifter communications require about 170 ms total critical path air time per message for the UPS system, including random access, plus ARQ and acknowledgements for reliable message transfer.

3.4.4. Multi-stop Package Tracking and Long Haul Arrival Reports

This message would typically contain about 250 bytes of data, including portions of package tracking reports for several customer stops. Vehicle monitoring and cargo manifest reports for long haul arrivals at hubs provide another example of a data message of this size.

This message length requires about 1.2 seconds of critical path air time for the UPS system.

3.4.5. Longer Messages or Harsher Channel Conditions

The scenarios given above assume good RF coverage, i.e. 95% FEC block success. Careful use of short, controlled data bursts enables the UPS system to adapt throughput to channel conditions. Capacity remains proportional to FEC block success rate, even in very harsh coverage conditions. As discussed in section 3.5., for most mobile data systems, throughput falls off much more rapidly in difficult coverage scenarios.

The most common planned UPS messages are inbound. For outbound messages, or as inbound transmissions grow longer, channel capacity depends less on multiple access methods and more on RF bit rate. However, efficient, reliable transfer of long messages still requires controlled data bursts for ARQ and acknowledgements.

The UPS system design includes means of segmenting long messages. Short packets and channel control signaling can readily be interspersed with segments of long transmissions.

The field tested baseline UPS system uses a 3/4 FEC code rate (i.e. 3/4 of the RF bits are data bits, while 1/4 are FEC parity bits) on the outbound link. Due to various additional signaling overheads, the effective inbound code rate is 1/2. The scenarios in sections 3.4.1.-3.4.4., and the comparisons in sections 3.5. and 3.6., include the effective 1/2 rate FEC. Future upgrade plans for the UPS system include a 3/4 code rate for both inbound and outbound links, which would make the efficiency comparisons in sections 3.5. and 3.6. even more favorable to the UPS 5 kHz digital FM system.

3.5. UPS 4 kbps/5 kHz FM System and 19.2 kbps/30 kHz System

An emerging system using a 19.2 kbps transmission rate in a 30 kHz channel provides a documented example of the general state of the art of mobile data communications. [24] Reference [24] specifies the packet data aspect of a voice-data system. Considering the system as it functions for data transfers, the packet communications are generally very similar to a number of current PLMR data systems for 12.5 to 25 kHz channels. The generic examples considered here provide a valid analysis of efficiency for whatever portions of time the system is used for data.

strictly minimizes the amount of time during which collisions are possible. This provides tremendous advantages for efficiently packetized information transfers.

The UPS system does not use contention for ARQ, whereas the 30 kHz system requires contention to regain channel access whenever a data block fails. Tables 2a and 2b compare the systems at 95% block success. For lower block success rates, the UPS system's throughput is directly proportional to the block success rate. Due to contention in case of block failures, the 30 kHz system experiences a rapid nonlinear reduction in throughput as block errors increase.

At 95% block success, overall coverage factors for the two systems are similar, and do not significantly affect efficiency comparisons. [9,24]

Results in Table 2a include the following factors: message size in bytes, hence number of bits; data bits and parity bits per FEC block, hence number of FEC blocks per message; RF bit rate; multiple access efficiency and overhead at 95% block success; ARQ; and other signaling, such as acknowledgements. Critical path RF air time refers to the inbound (reverse) channel for these applications. The analysis can be extended to consider the outbound (forward) channel as well. Relative spectrum efficiency in Table 2b is based on comparison of time x bandwidth products.

Table 2a. Comparison of RF Time x Bandwidth Efficiency
UPS 4 kbps/5 kHz FM Hybrid Multiple Access System
and 19.2 kbps/30 kHz CSMA System

Message Type	Size (bytes)	Average RF Air Time per Message (seconds)		Time x Bandwidth	
		5 kHz	30 kHz	5 kHz	30 kHz
Full Terminal Screen*	2048	8.9	1.9	44500	57000
Long Haul Arrival	250	1.2	.39	6000	11700
Package Track	100	.54	.27	2700	8100
Hub Shifter	20	.17	.21	850	6300
Vehicle Track**	4	.025	.21	120	6300

*This is not planned as a common UPS mobile data application, but is included to compare performance with a relatively long message.

**This is a specially compressed vehicle tracking message, using polling instead of random access in the 5 kHz system. The other applications shown here use random access in both systems.

**Table 2.b. Relative Spectrum Efficiency
Based on Time x Bandwidth for Data Messages
UPS 4 kbps/5 kHz FM Hybrid Multiple Access System
and 19.2 kbps/30 kHz CSMA System**

Message Type	Relative Spectrum Efficiency	
	5 kHz	30 kHz
Full Terminal Screen	100%	78%
Long Haul Arrival	100%	51%
Package Track	100%	33%
Hub Shifter	100%	13%
Vehicle Track	100%	2%
Relative Average	100%	35%

This comparison shows that wideband operation is not a requirement for mobile data system spectrum efficiency.

Spectrum efficiency of a 19.2 kbps/25 kHz system with other parameters similar to the 30 kHz system would be 45% relative to the 5 kHz system. As mentioned in section 3.4.5., practical steps for continued development can make the comparison even more favorable to the 5 kHz system.

3.6. UPS 4 kbps/5 kHz FM System and 64 kbps/25 kHz MQAM System

An emerging linear modulation and signaling technology for 25 kHz channels is described in a submittal to a European RF standards organization. [26] This system uses multicarrier QAM (MQAM) with a 64 kbps RF bit rate for digital voice and data. Due to the RF transmission rate and signal processing, delay spread is the main documented propagation impairment for the MQAM system, rather than Rayleigh fading.

As discussed in section 2.1.2.2., UPS digital FM technology has the basic capabilities to support digital voice within a 5 kHz channel. The MQAM system supports six voice channels within a 25 kHz bandwidth, for some advantage in voice channels per

unit bandwidth. However, data communications provide the greatest potential for improvement in overall land mobile spectrum efficiency, so, as in section 3.5., the comparison here focuses on data.

In section 3.5., the most significant factors in the spectrum efficiency comparison are the multiple access methods. In comparing the 64 kbps/25 kHz MQAM system with 4 kbps/5 kHz FM, coverage factors are very important, as well as bit rates, multiple access, and relative bandwidths.

3.6.1. Signaling Factors Affect Throughput

The RF air times for various lengths of messages in Table 3a include the following factors, drawn from the references on the respective systems: RF bit rates; random and reserved channel access; overheads such as block synchronization and guard times; FEC; and ARQ and acknowledgements for reliable data transfers. [26,9]

Both systems use efficient signaling methods. However, the UPS system uses smaller time x bandwidth increments, which provides advantages, especially for control signaling and short messages. Throughput is compared at 95% block success, i.e. about 10^{-2} BER.

3.6.2. Coverage Factors

MQAM requires linear amplifiers, whereas the UPS 4 kbps/5 kHz system is constant envelope, and can use nonlinear transmitters. As discussed in section 3.2.3., to compare link budgets for equal PEP, we use 2.5 dB as the peak to average power ratio for MQAM, based on single carrier 16 QAM. In fact, the multicarrier nature of MQAM causes a higher peak to average value than single carrier QAM. [26] Using 2.5 dB rather than a higher peak to average ratio biases the comparison somewhat in favor of MQAM.

Both the MQAM system and the UPS system can employ antenna diversity. We do not consider antenna diversity in comparing relative coverage.

In AWGN, per simulation results in [26], the MQAM system requires 10.5 dB E_b/N_0 at 10^{-2} BER, and 7.5 dB at 4×10^{-2}. With a 64 kbps RF transmission rate and 17.5 kHz 3

parameters for the UPS system are 9.5 dB at 10^{-2}, and 6.5 dB at 4×10^{-2}.

To complete the comparison, we consider MQAM performance in delay spread and 4 kbps/5 kHz FM performance in Rayleigh fading.

The most comparable delay spread performance figures for MQAM are simulated BER vs. E_b/N_0 results for 5 us rms delay spread at 450 MHz, although [26] mentions that the MQAM system is designed for up to 20 us rms delay spread. Other references in the literature cite larger values of delay spread observed in field tests or stated as system requirements, e.g. specifications at up to 41.7 us delay spread in [20].

The UPS system has been field tested under conditions where 10-50 us delay spreads are very common, and delay spreads of over 250 us have been observed. In field tests and simulations, delay spread effects on the UPS system are negligible.

Converting the MQAM BER vs. E_b/N_0 results from [26] for 5 us rms delay spread to C/N and C/I, we obtain 28 dB C/N or C/I at 10^{-2} BER, and 19 dB at 4×10^{-2}. Per [9] and recent results mentioned in section 2.1.2.2., comparable figures for the 4 kbps/5 kHz FM system in Rayleigh fading are 19.5 dB at 10^{-2}, and 11.5 dB at 4×10^{-2}.

The net relative link budget advantage for the UPS 4 kbps/5 kHz FM system is 9 dB in AWGN and about 10.5 dB in difficult propagation environments. Using the rules of thumb in section 3.2.2., the overall relative coverage comparison is 100% for the UPS 4 kbps/5 kHz FM system and 40% for the MQAM system.

Table 3a. Comparison of RF Time x Bandwidth Efficiency
UPS 4 kbps/5 kHz FM System and 64 kbps/25 kHz MQAM System

Message Type	Size (bytes)	Average RF Air Time per Message (seconds)		Time x Bandwidth	
		5 kHz	25 kHz	5 kHz	25 kHz
Full Terminal Screen*	2048	8.9	.61	44500	15250
Long Haul Arrival	250	1.2	.12	6000	3000
Package Track	100	.54	.069	2700	1725
Hub Shifter	20	.17	.053	850	1325
Vehicle Track**	4	.025	.016	125	395

*This is not planned as a common UPS mobile data application, but is included to compare performance with a relatively long message.

**This is a specially compressed vehicle tracking message, using polling instead of random access with both systems. The other applications shown here use random access.

Table 3b. Relative Spectrum Efficiency
UPS 4 kbps/5 kHz FM System and 64 kbps/25 kHz MQAM System
Based on Time x Bandwidth and Relative Coverage

Message Type	Relative Spectrum Efficiency	
	5 kHz	25Hz
Full Terminal Screen	86%	100%
Long Haul Arrival	100%	80%
Package Track	100%	63%
Hub Shifter	100%	26%
Vehicle Track	100%	13%
Relative Average	100%	58%

For longer messages, the MQAM system attains a time x bandwidth advantage, but this is outweighed in the overall comparison by the coverage advantages of the UPS 5 kHz FM system. Improved coding and higher data rates under development for the UPS system can make the comparison even more favorable for 5 kHz digital FM technology.

3.7. Throughput and Coverage Comparisons, Narrowband Systems

Sections 3.5. and 3.6. examined spectrum efficiency impacts of different bandwidths, bit rates, multiple access systems, and coverage factors. Section 3.7. considers throughput and coverage differences for different modulations in a 5 kHz bandwidth.

We assume a highly efficient multiple access system in comparing different modulations. Adaptability to efficient multiple access and ARQ methods is a major criterion for comparing different modulations. Of the modulations discussed here, the one with the most explicit published discussion of its use in a highly efficient data system is UPS's digital FM technology. We assess the adaptability of other modulations to efficient data systems based on our own experience and published material in the literature.

3.7.1. Pilot Tone Techniques: TTIB, ACSSB

3.7.1.1. Pilot Tones and Packet Data Operations

TTIB and ACSSB use a pilot tone to compensate for Rayleigh fading in narrowband

The British MPT 1327 trunking standard mentioned in [13] provides an interesting example of mixed mode operation, with FFSK control signaling used to establish a circuit for TTIB/QAM message transmission or other data or voice modulation. However, depending on the exact scenario, MPT 1327 would add 320 ms to 530 ms to critical path air time, with further synchronization, ARQ, and acknowledgement signaling still required for the actual data transfer. [29]

In Table 4 and Table 5, for the fairest comparison between narrowband digital FM and other narrowband digital modulations, we make the evaluation within the framework of the UPS signaling design. The throughput comparisons reflect both the bit rate of the respective modulations, and their ability to support efficient data signaling.

Table 4. Relative Efficiency Based on RF Air Time
UPS 4 kbps/5 kHz FM and 9.6 kbps/5 kHz TTIB/QAM
Varying Data Message Sizes

Message Type	Message Size (bytes)	Average RF Air Time Per Message (seconds)		Relative Efficiency	
		4 kbps FM	9.6 kbps TTIB/QAM	4 kbps FM	9.6 kbps TTIB/QAM

3.7.1.3. TTIB/QAM and Narrowband FM Relative Coverage Factors

Results in [13] focus mainly on 1.2 kbps digital performance with TTIB. For 9.6 kbps transmission, TTIB uses 16 QAM, which in turn uses two four level AM waveforms in phase quadrature. As shown in [30], four level AM requires 9 dB E_b/N_0 for 10^{-2} symbol error rates in AWGN. With Gray coding, the four level AM symbol error rate equates for practical purposes to BER for 16 QAM.

In [6], qualitative results show that TTIB reduces but does not eliminate the Rayleigh fading effect of increased E_b/N_0 required for BER values on the order of 10^{-2}. For comparison, we estimate a 5 dB Rayleigh fading effect at 10^{-2} BER for 9.6 kbps

3.7.2. DAPSK

Differential Amplitude Phase Shift Keying (DAPSK) is a linear modulation without pilot tones, which can attain high data rates and quick detection in narrowband channels. Per analytical results in the literature, the tradeoff is reduced coverage. DAPSK can attain 2.3 bits per second per Hz, for 9.2 kbps in a 4 kHz authorized bandwidth. For 10^{-2} BER, DAPSK requires 15 dB E_b/N_0 in AWGN, with Rayleigh fading causing a further 10 dB degradation at 10^{-2} BER. [18]

Link budget comparisons for 9.2 kbps DAPSK and 4 kbps FM give a net result of 11.5 dB in favor of FM at 10^{-2} BER: 9.5 dB E_b/N_0 for 4 kbps FM, 15 dB for 9.2 kbps DAPSK [18]; 2 dB for DAPSK peak to average power ratio; and 4 dB for relative data rates. The dB difference does not change for Rayleigh fading vs. AWGN, and the interference limited comparison is very nearly the same as the power limited case.

3.7.3. RZSSB

RZSSB does not use pilot tones. It typically relies on mobile antenna diversity in Rayleigh fading, which is somewhat of an added cost factor. Stated digital applications planned to date for RZSSB do not include packet data. [7] We assume here that the burst spectrum of RZSSB can be controlled, and that RZSSB can be adapted to efficient detection of controlled bursts, though these areas are not mentioned in available reports on RZSSB implementation.

3.7.3.1. RZSSB with 16 QAM, 9.6 kbps

Link budget comparisons for 9.6 kbps RZSSB/QAM and 4 kbps FM give a net result of 8.5 dB in favor of FM at 10^{-2} BER in AWGN: 9.5 dB E_b/N_0 for 4 kbps FM, 12 dB for 9.6 kbps RZSSB/QAM [7]; an estimated 2 dB for RZSSB/QAM peak to average power ratio, since RZSSB uses a low AM index for RF modulation; and 4 dB for relative data rates.

In Rayleigh fading, the difference becomes 14.5 dB in favor of FM, since RZSSB degrades more in Rayleigh fading than FM. [7] Both modulations can attain improved performance with diversity, but diversity has been omitted to keep the comparison as generic as possible.

3.7.3.2. RZSSB with 128 QAM, 19.2 kbps

Link budget comparisons for 19.2 kbps RZSSB/QAM and 4 kbps FM give a net result of 18.5 dB in favor of FM at 10^{-2} BER in AWGN: 9.5 dB E_b/N_0 for 4 kbps FM, 19 dB for 19.2 kbps RZSSB/QAM [7]; an estimated 2 dB for peak to average power ratio; and 7 dB for data rate.

For Rayleigh fading, [7] only includes 19.2 kbps results with diversity. The difference becomes 14.5 dB in favor of FM, since this comparison considers FM without diversity and assigns a higher relative complexity factor to 19.2 kbps RZSSB in Table 4.

3.7.4. π/4 QPSK for 5 kHz Channels

In this discussion, we consider π/4 QPSK with discriminator or differential detection, for best performance in efficient data systems.

Link budget comparisons for 4 kbps π/4 QPSK and 4 kbps FM give a net result of 2.5 dB in favor of FM at 10^{-2} BER in AWGN: 9.5 dB E_b/N_0 for 4 kbps FM, 7 dB for π/4 QPSK, based on simulation results in [31]; and 5 dB for π/4 QPSK peak to average power ratio. [17]

In Rayleigh fading, the net advantage becomes 4.5 dB for FM. FM requires about 10 dB higher E_b/N_0 at 10^{-2} BER in Rayleigh fading as compared to AWGN. Based on simulated C/N results in [32], adjusted for relative data rates and estimated noise bandwidth, π/4 QPSK requires about 12 dB higher E_b/N_0 at 10^{-2} BER in Rayleigh fading as compared to AWGN.

Based on [17] and on simulations done in support of [8], π/4 QPSK can attain up to about 6 kbps in 5 kHz channels. The link budget comparison with 4 kbps FM changes by 2 dB in favor of FM due to the change in data rate. However, as shown in Table 5, 6 kbps π/4 QPSK has better area coverage than 6 kbps FM.

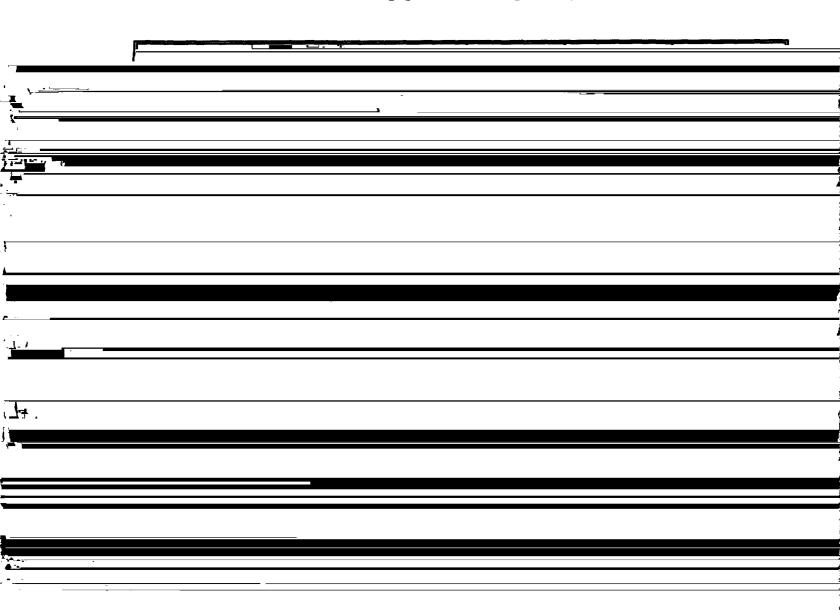### 3.7.5. Multiple Data Rates with Narrowband FM

Recent II Morrow lab results show that 6 kbps narrowband FM attains a 6.5 dB less favorable link budget as compared to 4 kbps narrowband FM, due to data rate and details of modulation parameters. The difference at 1 kbps vs. 4 kbps is 6 dB in favor of

1 kbps, due to the difference in data rates. Analysis is proceeding for constant envelope data rates higher than 6 kbps in 5 kHz channels, but results are preliminary at this time.

3.8. Tabulated Relative Data Efficiency for Narrowband Modulations

As mentioned in 3.7.1.2., for the fairest comparison between narrowband digital modulations, relative efficiency is evaluated assuming the same framework of efficient packet data signaling for all modulations.

Table 5. Relative Spectrum Efficiency for 5 kHz Digital Modulations Based on Data Throughput and Coverage Comparison

[27,28]

***RZSSB 19.2 kbps coverage includes antenna diversity. Other modulations can also improve performance with diversity, but diversity is not included in any of the other results shown here.

3.9. Observations on Relative Spectrum Efficiency

All the narrowband modulations in Table 5 show better overall relative spectrum efficiency than the 30 kHz and 25 kHz CSMA system examples evaluated in Table 2b and the paragraphs just after it. Most of the narrowband modulations show better overall relative spectrum efficiency than the MQAM system evaluated in Table 3b.

Tables 2a, 2b, 3a, 3b, 4, and 5 illustrate the overall throughput and coverage advantages of UPS's narrowband FM mobile RF packet data technology. The only technology which attained a higher overall score in any of the comparisons was 19.2 kbps RZSSB, and the possible advantage comes at the price of significantly more complex equipment and greatly reduced coverage. Also, narrowband FM has already been type accepted at 220 MHz and integrated into a field tested mobile packet data system. Published RZSSB results to date do not include burst spectrum control or integration into packet data systems.

This does not mean that there is only one answer for spectrum efficiency. The comparison methods shown here can be extended to other types of applications, with potentially different results. However, many other mobile radio users have requirements similar to those of UPS. UPS fully expects mobile packet data communications to become increasingly widespread over the next several years.

II Morrow continues to work to improve UPS's 220 MHz technology. Enhanced modulation, higher data rates, and digital voice for narrowband FM are the most recent accomplishments. Further design goals include increased throughput and coverage by combining desirable properties of multiple modulation modes within the same channel or group of channels. II Morrow looks forward to the ongoing challenge of furthering the evolution of practical, state of the art mobile communications technology.

3.10. Potential Alternative: Market Driven Spectrum Efficiency

The comparisons above can be reduced to a simple equation:

$$\text{spectrum efficiency} = \frac{\underline{\text{useful throughput x coverage capability}}}{\text{time x bandwidth}}$$

Throughput, coverage, and use of time x bandwidth spectrum resources depend on a number of parameters, some of which may not be obvious. However, valid comparisons can be made, provided that the applications and technologies of respective systems are reasonably well understood.

As shown in the preceding pages, a wide variety of mobile radio technologies can be adapted for compatible use within the framework of a well crafted set of emission rules.

Pending legislation may impact the role of FCC spectrum efficiency criteria in radio channel licensing. An alternative is to establish compatibility for a variety of technologies through well crafted emission rules, and then let the respective markets for spectrum and equipment determine what cost effective spectrum efficiency means to the users.

Conclusion

In conclusion, UPS wants to briefly restate the three important themes mentioned in the Introduction, and touched on repeatedly in the body of these Reply Comments.

First:

The 220 MHz narrowband emission rules allow the use of a very broad variety of modulation technologies, and provide a fully viable standard for compatibility between diverse technologies. Adding provisions for flexible use of contiguous channel blocks would open even greater options for efficient spectrum use, with very large scale systems attainable within relatively small amounts of regionally or nationally licensed spectrum. Different modulations and bandwidths, cost effectively tailored to the spectrum efficiency requirements of different users, can exist side by side in the same band. At 220 MHz, the FCC did an excellent job of melding a number of inputs into practical rules and test standards allowing full use of adjacent channels, and high performance within each channel.

Second:

The growing list of type accepted 220 MHz radios and the published results of other narrowband developers provide visible evidence that varied approaches to the use of land mobile RF channels as narrow as 5 kHz are attaining practical fruition.

Third:

UPS's type accepted 220 MHz narrowband digital FM radios and system technology have already shown dramatic improvements in cost effective spectrum efficiency in field tests of practical mobile data communications applications.

UPS looks forward to the realization of similar improvements for all refarmed bands.

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[26] "Mobile Digital Trunked Radio System," proposal to ETSI STC/RES-6, submitted by Motorola European Research Laboratory in response to Feb. 22, 1991 request for proposals.